THE PRODUCTION OF DIORITIC MAGMAS BY FLUID INFILTRATION IN THE PLUTONIC IGNEOUS COMPLEX AT SOREL POINT, JERSEY, CHANNEL ISLANDS

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The plutonic igneous complex at Sorel Point, Jersey, Channel Islands. comprises a variety of rocks within the compositional spectrum gabbro-diorite-granodiorite-granite. Four temporally separable rock groups are present within the complex, each consisting of a number of lithologies which were originally present as coexisting magmas. Geochemical data confirms field, petrographic and mineralogical evidence that dioritic rocks were produced by infiltration of volatile-rich residual granitic liquids into coexisting gabbroic magmas. The compositional and mineralogical effects of this process decrease systematically with increasing distance from the original acid-basic magma interface. The selective and inhomogeneous nature of the process is demonstrated by non-linear trends and considerable scatter on variation diagrams.

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INTRODUCTION

The close association of acid and basic rocks in plutonic environments, together with evidence of physical and chemical interaction between them, is a widespread and widely reported phenomenon (e.g. Wiebe, 1980; Furman and Spera, 1985; Brown and Becker, 1986; Barbarin, 1988; D'Lemos, 1986, 1992, 1996; Cook, 1988; El Desouky *et al.*, 1996; Baxter and Feely, 2002). Physical constraints, such as viscosity contrast, inhibit the ability of the magmas to mix so that they survive as discrete entities with stable interfaces between them.

Chemical interaction between the magmas can take place up to (and possibly below) the point at which one of them reaches its solidus. Interaction may take the form of fluid or diffusional infiltration, or a combination of both. However, the slow rates at which diffusion is known to occur, mean that it has the capacity to affect only relatively small volumes either side of a magmatic interface. In order for larger volumes to be affected a process of fluid infiltration is required. During this process, fluid is able to physically cross the interface from one magma to the other.

The aim of this paper is to describe the geochemical variation seen in a group of closely related rocks from the Sorel Point Complex, and to discuss the nature of the post-emplacement interactions which brought about these variations. An important consequence of the interactions was the production of dioritic magma from gabbroic magma.

THE GEOLOGY OF SOREL POINT

Sorel Point lies on the north coast of Jersey, Channel Islands and consists of calc-alkaline plutonic rocks emplaced during the latter stages of the Cadomian orogeny (D'Lemos *et al*, 1990, 1992). The Sorel Point Complex consists of a variety of rock types within the compositional spectrum gabbro-diorite-granodiorite-granite (Figure 1). Detailed field and petrographic descriptions are given in Salmon (1998). The rocks of the complex can be divided into four temporal groups (A to D) representing four separate intrusive episodes, with Group A being the earliest. Each group comprises at least two lithologies with contact relationships indicative of coexisting magmas. The intrusive episodes are separated by the time required for the

preceding group of magmas to cool and solidify, so that contacts between the intrusive groups are planar and angular (i.e. brittle) in nature. The rocks of Sorel Point thus record an extended and complex history of magmatic intrusion and interaction (Salmon, 1998).
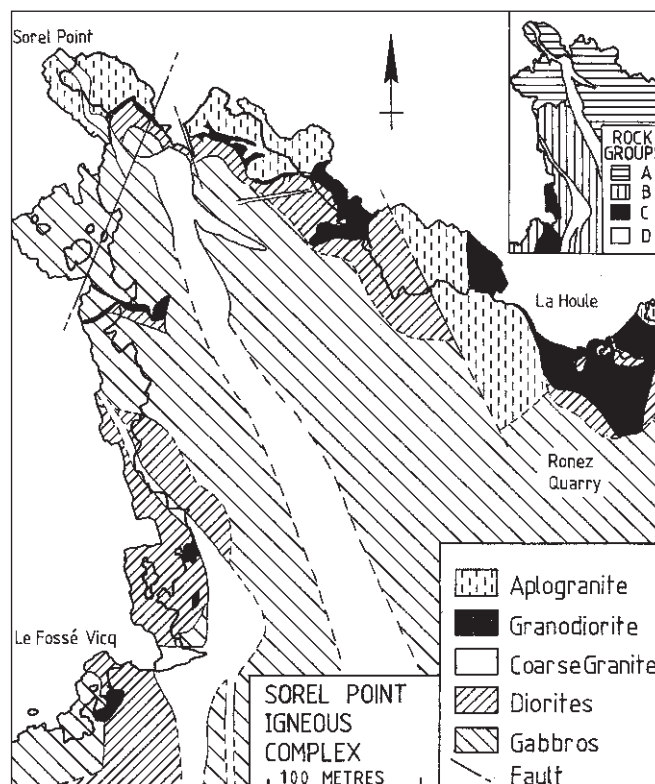
Figure 1. *Simplified geological map of Sorel Point (from: Salmon, 1996, 1998). The inset shows the extent of rock groups A to D referred to in the text.*

This paper concentrates on rocks of Group A (Figure 1), in which miarolytic pink aplogranite is separated from overlying mafic rocks by a sheet of granodiorite, which varies in thickness up to 3 m and sends numerous offshoots into the mafic rocks (Figure 2). The granodiorite comprises tabular feldspar megacrysts, *c*. 1 cm long, in an anhedral granular groundmass. The feldspar megacrysts display disequilibrium phenomena, such as cellular growth morphologies and rapakivi textures, typical of those found in hybrid rocks (Hibbard, 1991). Most of the granodiorite offshoots are sinuous and less than *c*. 15 cm wide. Others take the form of cylindrical pipes, usually *c*. 15 cm in diameter, which may extend for several metres and plunge *c*. 45°N (Salmon, 1996). Where the upper terminations of pipes are exposed they are filled with granite pegmatite. Pegmatite pods of various sizes are present throughout the granodiorite, often concentrated immediately beneath the granodiorite-diorite interface. The granodiorite sheet (which marks the acid-basic contact) dips *c*. 45°S but can be shown from the attitude of the pipes (which are density-controlled structures and were originally vertical) to have been originally horizontal (Salmon, 1996). The mafic rocks pass gradationally (over a distance of *c*. 14 m) from diorite (s.s.), through a transitional diorite facies to hornblende gabbro. The interface between the granodiorite and diorite is lobate, undulose or crenulate in form (Figure 3) with the diorite having a fine-grained chilled margin. Small flame structures pierce the chilled margin and convey felsic material from the granodiorite into the mafic rocks above. Contact relationships indicate that all of the rocks of Group A were present as coexisting magmas (Salmon, 1998).

Textural and mineralogical variations in the mafic rocks occur systematically with increased distance from the granodiorite/diorite interface (Salmon, 1998). This is manifested by a gradual increase in grain size; by a change in texture, from equigranular in the diorite adjacent to the granodiorite to ophitic in the hornblende gabbros; and by changes in modal composition. The diorites consist predominantly of plagioclase and unzoned hornblende, in the transitional diorite, individual amphiboles are zoned from hastingsitic cores through hornblende zones to actonilitic rims (Salmon, 1991) and in the hornblende gabbro similarly zoned amphiboles have clinopyroxene present as irregularly-shaped cores. The transitional diorites contain hornblende-mantled quartz ocelli and acicular apatite, both phenomena commonly associated with magma-mixing and hybridization processes (Hibbard, 1991; Baxter and Feely, 2002). Sericitization of plagioclase is widespread.

Amphibole geobarometry has shown that the magmas were emplaced at shallow (<2.5 Kb) crustal levels (Salmon, 1992). The Sorel Point Complex thus represents the remnants of a shallow sub-volcanic magma chamber system, which was constantly evolving over an indeterminate period of time. It is likely that the distinct intrusive groups at Sorel Point belong to successive eruptive cycles, with a number of small batches of magma entering the system during each cycle. The eruptive cycles were separated by periods of quiescence, during which the volcano may have been dormant and the magmas emplaced during the preceding eruptive cycle cooled and crystallized.

GEOCHEMISTRY

A large number of rock samples were collected for geochemical analysis. This was carried out at Oxford Polytechnic (now Oxford Brookes University) using inductively coupled plasma source spectrometry and atomic absorption source spectrophotometry. Selected analyses of rocks from Group A are given in Table 1 (a complete set of analyses are available from the author upon request). Representative chemical variation diagrams are presented in Figure 4.

Although the quite closely constrained trend displayed by MgO might initially suggest that the rocks represent a fractionation sequence, the patterns shown by most other oxides and elements indicate that this is not the case. TiO_2 and V
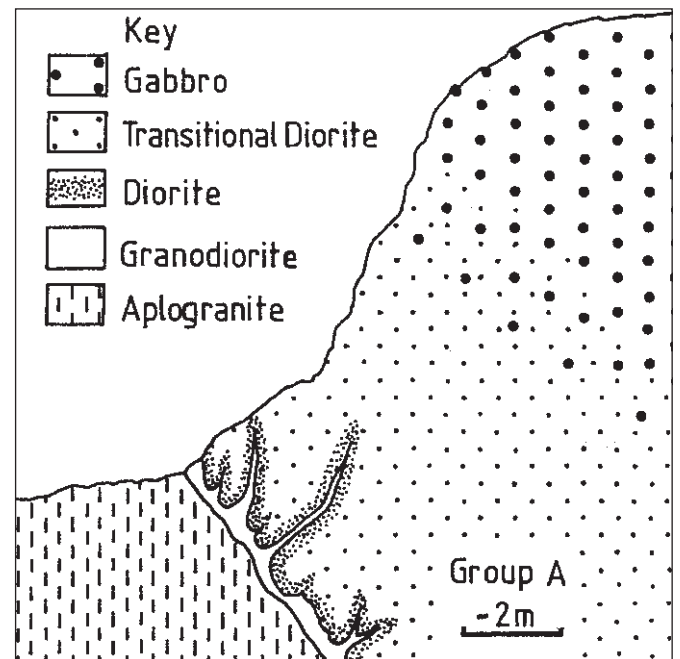
Figure 2. *Schematic vertical cross-section through the rocks of Group A at the north end of Sorel Point (from: Salmon, 1996). Note that the scale is approximate.*
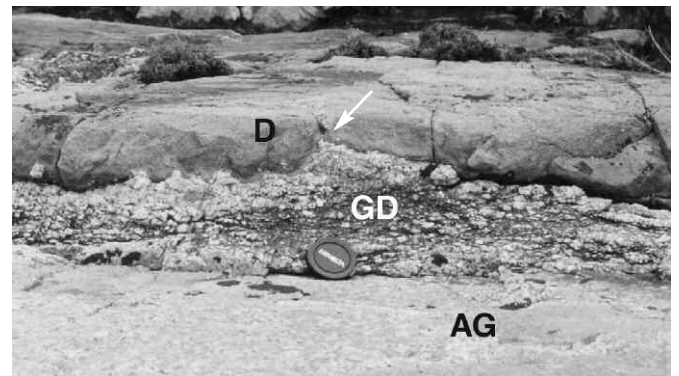
Figure 3. *Typical crenulate contact between diorite (D) and granodiorite (GD), which separates it from the aplogranite (AG). Arrow indicates one of the 'flame' structures referred to in the text.*

show a marked inflection at *c*.52% SiO_2, with a well constrained negative correlation with SiO_2 in all rocks except the hornblende gabbro. Na_2O, Ba and Zr show a marked inflection at *c*. 69% SiO_2, with the aplogranite plotting in a discrete group and the granodiorite and diorites displaying considerable scatter. Two distinct trends are evident on the Na_2O-K_2O diagram, with the scattered values of the aplogranite and granodiorite lying on a trend which is separate to the relatively condensed trend of the gabbro and diorites.

Sampling of the diorite and transitional diorite was carried out at varying distances from the granodiorite/diorite interface. The compositions were then normalised to an average composition of four samples of the hornblende gabbro. These gabbros were sampled at relatively large distances from the granodiorite/diorite interface, and hence are assumed not to have been affected to any large degree. Thus, they give the closest available compositions to the original magma. Selected oxides and trace elements are plotted against distance in Figure 5. The figure of 1.0 on the vertical scale represents the normalising composition (i.e. the average composition of the unmodified magma), values >1.0 indicating relative enrichment, <1.0 relative depletion. Because of sample resolution and other constraints, the resultant diagrams cannot give fine-scale

Sample No	77C	57A	88M	89K	77A	77H	89G	56A	77G
Rock type	AG	AG	GD	GD	Df	TD	TD	HG	HG
SiO_2	77.75	77.57	68.41	68.43	55.38	50.92	52.00	50.84	51.37
TiO_2	0.05	0.05	0.66	0.47	1.84	1.48	1.54	1.60	1.43
Al_2O_3	12.24	12.11	15.57	15.48	16.09	16.04	15.91	15.70	15.03
FeO(T)	0.90	0.95	4.05	3.58	9.37	9.21	8.90	9.46	9.00
MnO	0.01	0.01	0.07	0.07	0.17	0.17	0.17	0.17	0.17
MgO	0.15	0.17	1.33	0.82	3.61	7.10	6.21	7.56	8.11
CaO	0.13	0.12	3.14	2.36	6.60	8.72	8.44	8.59	9.22
Na_2O	3.95	3.37	4.46	4.57	4.30	3.53	3.56	3.17	3.20
K_2O	4.41	5.35	1.85	3.48	1.18	0.74	1.19	0.75	0.62
P_2O_5	0.01	0.01	0.17	0.18	0.31	0.23	0.25	0.19	0.19
H_2O	0.38	0.33	1.04	1.00	1.41	1.79	1.91	1.80	1.87
Total	99.98	100.22	100.75	100.44	100.29	99.93	100.08	99.83	100.21
Ba	45	40	384	561	318	134	171	132	119
Ce	37	43	44	50	50	21	33	24	16
Cr	16	21	29	28	37	100	121	118	195
Cu	4	10	6	10	46	74	57	63	107
La	n.d	18	28	27	33	33	31	31	32
Li	3	n.d.	28	26	30	25	28	25	59
Nb	5	7	14	8	11	10	10	11	9
Ni	n.d	n.d.	7	5	n.d	50	24	56	59
Rb	133	81	92	160	38	17	34	25	17
Sc	2	3	11	8	29	36	35	38	41
Sr	7	7	190	152	261	265	264	271	266
V	1	3	60	33	242	295	241	260	300
Y	25	40	30	34	42	37	32	24	33
Zr	103	150	244	264	170	111	149	112	108

Key to rock types:

AG – aplogranite; GD – granodiorite; Df – diorite, fine-grained margin; TD – transitional diorite; HG – hornblende gabbro.

Table 1. *Selected geochemical analyses for rocks of Group A. Oxides are given in weight percent, trace elements in parts per million.*

representations of chemical gradients. However, they do indicate compositional changes across the body of rock, but as a 2-D traverse rather than a 3-D view.

On these diagrams (Figure 5), SiO_2, Na_2O and K_2O all plot above 1.0, while TiO_2, FeO(T) and MnO mostly plot above 1.0. SiO_2 and Na_2O increase steadily in value as the contact is approached. The differences may appear small, but it should be borne in mind that an increase of 0.1 for SiO_2 is equivalent to *c.* 5 wt%. Both TiO_2 and MnO have their highest values at distances of 40 to 50 cm from the contact. Ba and Y, and most Ce, La, Rb and Zr values plot above 1.0, with Ba, Ce and Y showing a general increase towards the granodiorite-diorite contact. Several elements, notably Ba and Rb, have high values, up to 5 times the average hornblende gabbro composition.

POST-EMPLACEMENT MAGMATIC EVOLUTION

Field, petrographic and mineralogical evidence (Salmon, 1987, 1991, 1992, 1998) indicates that the dioritic rocks of Group A were produced *in-situ*, following emplacement, by interactions between the coexisting gabbroic and granitic magmas. Similar processes have occurred elsewhere throughout the complex (Salmon, 1992). Field relationships suggest that

the hornblende gabbro was the basic end member. The most obvious candidate for the acid end member is the granodiorite. However, the aplogranite appears to have played an important part. The presence of miarolitic cavities in the aplogranite, together with pegmatite in the granodiorite, indicate the presence of a fluid phase, much of which appears to have originated in the aplogranite. This fluid phase, driven by bouyancy effects, entered the granodiorite magma, combining with its residual fluids. This process would explain the well-constrained trend linking the two rocks on the Na_2O-K_2O diagram (Figure 4). The resultant fluid then ponded beneath the stable granodiorite-diorite interface, ultimately forming the pegmatite pods referred to above.

There are two main processes which could have been responsible for the post-emplacement evolution of the mafic magmas. These are: (1) magma-mixing, and (2) fluid and/or diffusional infiltration. True mixing can only take place between two magmas that have similar rheological properties. So, although density differences between the various coexisting magmas might be expected to lead to instability, overturn and subsequent physical mixing, this tendency would be inhibited by the large viscosity contrasts which also existed (Salmon, 1996).
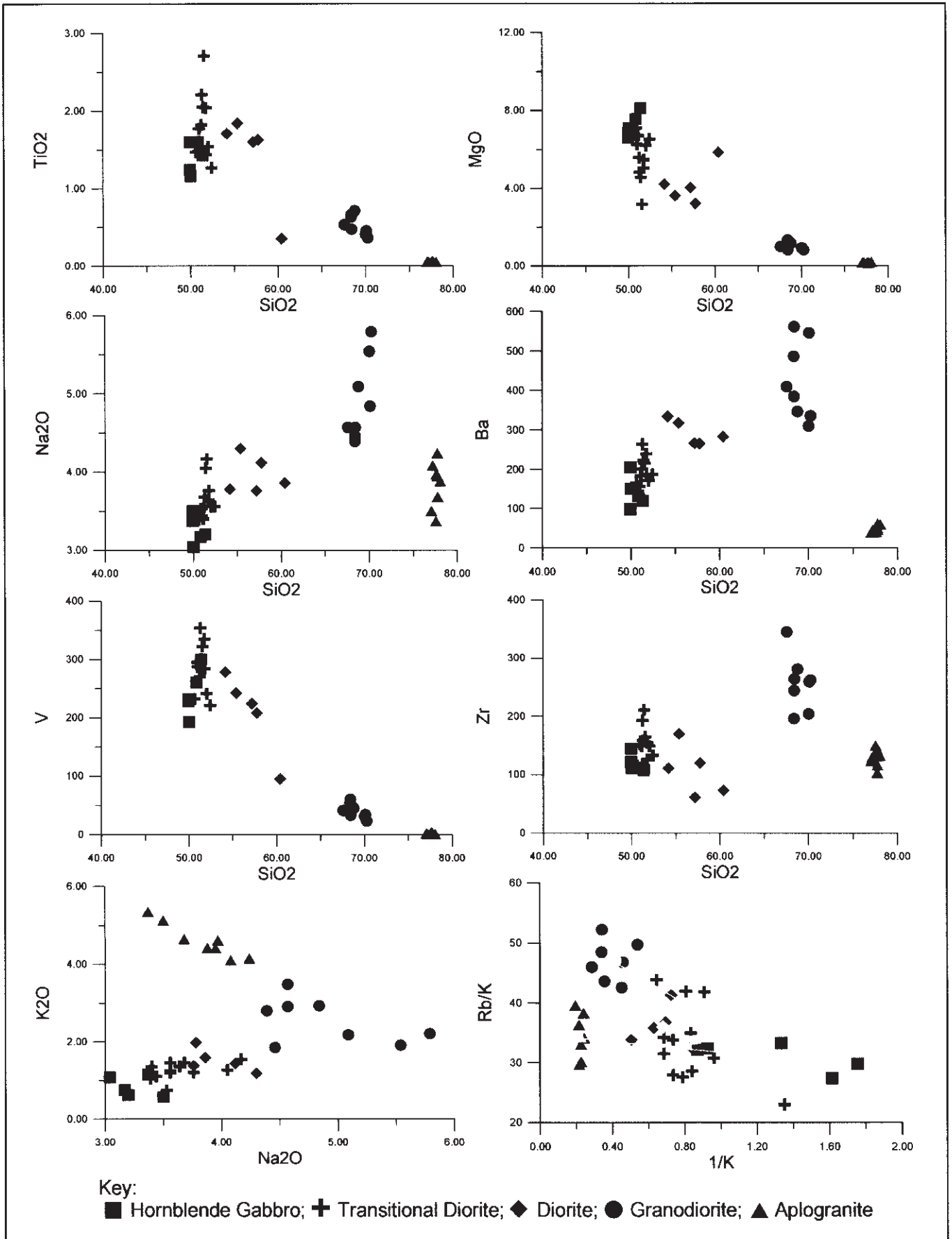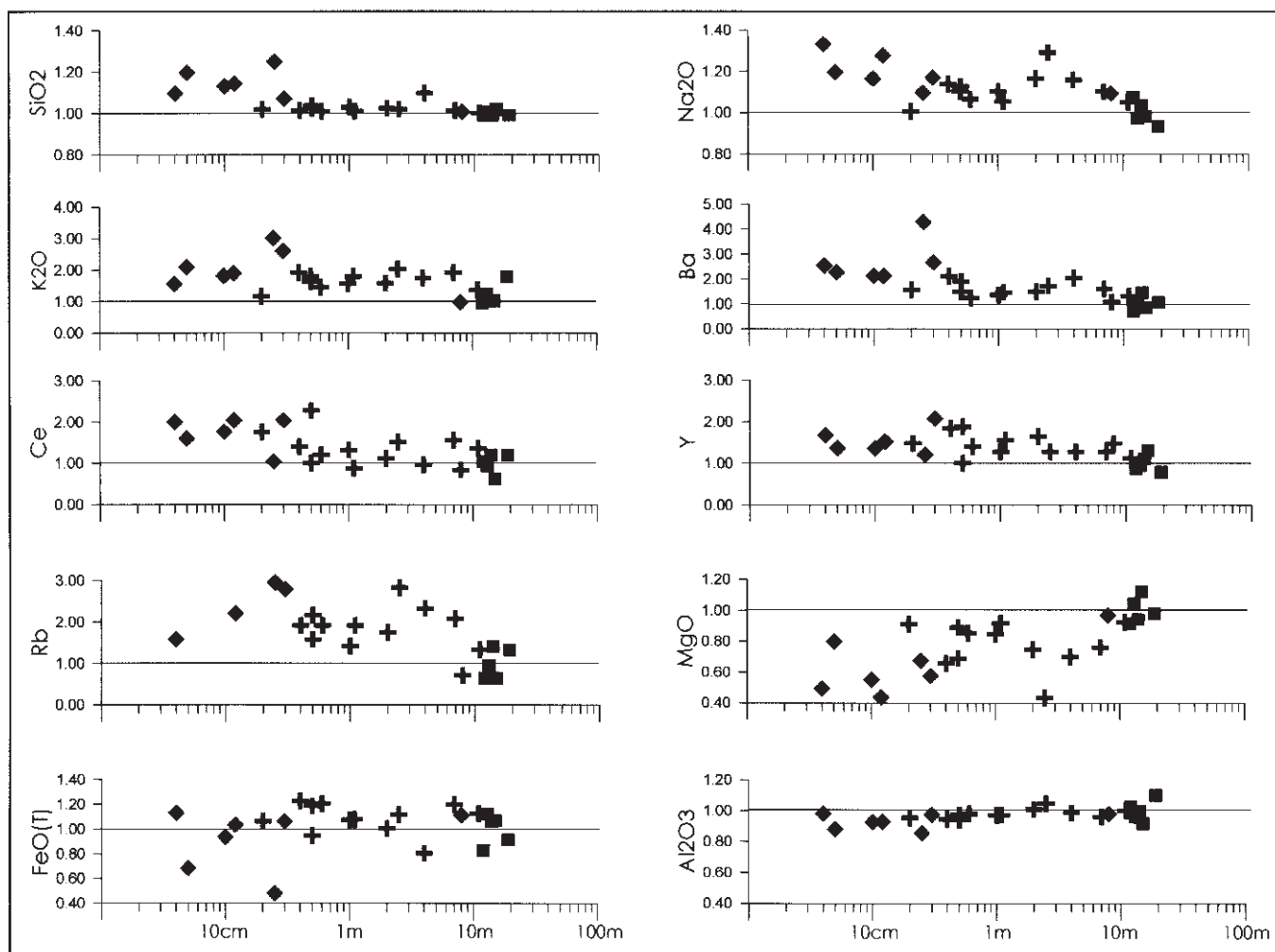
Figure 4. *Selected geochemical variation diagrams for rocks of Group A. Major element oxides (wt %) and trace elements (ppm) are plotted against wt % SiO₂. The oversize, grey symbols on the Rb/K vs 1/K diagram are mean compositions of the samples plotted, with 'mixing' lines drawn between certain potential end-members.*

Figure 5. *Mafic rocks of Group A normalised to an average hornblende gabbro composition and plotted against distance (logarithmic scale) from the granodiorite-diorite interface (symbols as in Figure 4).*

The almost ubiquitous presence of granodiorite between the aplogranite and diorite has led to the suggestion that it is a product of mixing between them. This can be ruled out by consideration of the geochemical evidence. On simple binary diagrams, the product of magma mixing should lie on a straight line drawn between the two parent end-members. The Na_2O, Ba, Zr and Na_2O-K_2O diagrams clearly demonstrate that the granodiorite could not have been produced by simple mixing between the aplogranite and any of the mafic rocks. This is further demonstrated by the Rb-K diagram, which is considered by Langmuir *et al.* (1978) to be a good test of magma mixing. On the Rb-K diagram, hybrid rocks should again plot on a straight line between the end-members. The granodiorite plots well away from such a line linking the aplogranite and the mafic rocks.

A magma mixing origin for the transitional diorite also needs to be considered. The only available basic end-member is the hornblende gabbro, with both the granodiorite and aplogranite being potential acid end-members. Consideration of the Na_2O, Ba, Zr and Na_2O-K_2O diagrams clearly rules out the aplogranite. Close examination of the TiO_2, MgO, Na_2O, V and Rb-K diagrams shows that most of the transitional diorite samples plot away from a mixing line linking the gabbro and granodiorite. So, the chemical evidence indicates that the transitional diorite was not produced by simple magma mixing.

The only one of the rocks from Group A that displays any convincing geochemical evidence for an origin by magma mixing is the diorite, with the granodiorite and the transitional diorite as end-members. However, the Zr diagram throws some doubt upon this, as the diorite samples plot below a line linking these rocks. It is also considered unlikely given the field relationships and the fact that most of the diorite samples are from the fine-grained margins. It is more likely that the chemical juxtaposition is due to the process of fluid infiltration, with fluids passing upwards (driven by density contrasts) from the granodiorite into the overlying mafic magmas. As all of this fluid had to pass through the marginal diorite, it is to be expected that is reflected in its chemical composition.

The bulk rock compositional variations are reflected in the chemistry of amphiboles, the predominant ferro-magnesian mineral in the diorites and the gabbro (Salmon, 1991). The amphiboles show a systematic bulk chemical variation with distance from the granodiorite, as well as a core-to-rim chemical zonation in individual amphiboles. Of particular note are the variables (K/Na+K)(AMPH) and (K_2O/Na_2O+K_2O)(ROCK), both of which decrease with distance from the granodiorite (Salmon, 1991). As potassium is present in residual granitic liquids, and would be reflected in amphibole compositions, the decreasing trends lend further support to the fluid infiltration model.

DISCUSSION

The extent of any magmatic interactions which may take place in shallow crustal environments will ultimately be limited by the relatively short periods of time required for magma to cool and solidify. At the depths indicated by amphibole geobarometry for Sorel Point, the small batches of magma being introduced into the system would have solidified in thousands (or tens of thousands) of years, rather than millions.

Diffusion rates in magmas are known to be slow (e.g. Baker, 1990; Lesher, 1994) and although enhanced by the presence of H_2O and other volatiles (Baker, 1991; Lesher, 1994), diffusion has the ability to affect only small volumes, given typical magmatic cooling rates. This severely limits the extent of any interactions which can be achieved by diffusion alone and rules out chemical diffusion as the dominant process at Sorel Point.

Although also limited by the time constraints discussed above, the process of fluid infiltration has the ability to affect relatively large volumes of magma. Infiltration of volatile-rich granitic fluids through a partially crystalline basic magma is analogous to the process of "postcumulus magmatic infiltration metasomatism" of Irvine (1980). The presence of infiltrating liquid within the interstices of the chilled margin and the basic magma beyond will enhance chemical diffusion rates, allowing this process to have a complementary effect. Petford *et al.* (1996) have shown that advective transfer of fluids is an efficient mechanism of chemical exchange between mafic enclaves and a granitic host.

However, magmatic fluid infiltration can only take place if the passage of fluids into the basic magma is unhindered. One potential barrier to this free movement is the presence of a chilled margin in the basic magma. If this were completely crystallized, chemical interaction across the interface would only be possible by diffusional exchange (Barbarin, 1988). However, the "flame" structures that cross-cut the chilled margins of the diorites clearly convey material from the granodiorite into the diorite and the mafic rocks beyond (Salmon, 1998). Furthermore, infiltration may also occur through the chilled margin itself. The presence of any residual intercrystalline liquid would render the chilled margin permeable and allow infiltration to take place. Holden *et al.* (1991), discussing the rheology of mafic enclaves in felsic host magmas, suggest that mafic enclaves may "crystallize to a point where structural integrity is assured but fluid/magma passage through the [crystal] aggregate is not prevented". The same could be equally said of the chilled margins.

A number of authors (e.g. Orsini *et al.*, 1991; Platevoet and Bonin, 1991; Zorpi *et al.*, 1991; D'Lemos, 1992, 1996) have described processes of volatile-rich fluid infiltration from acid to basic magma, resulting in modification of the melt compositions (especially that of the basic melt). The process enriches the basic magma in elements such as Si, K, Li, Rb, Y, Zr and REE (along with volatiles, especially H_2O). In the Permian alkaline province of Corsica, a process of interaction between coexisting gabbro and granite magmas has resulted in enrichment of the gabbroic magma in alkalis, Fe, Ti, Rb, Sc, V, Y, Zn, Zr and LREE (Platevoet and Bonin, 1991). The granite was depleted in alkalis, Rb and Y, but enriched in Ba, Sr and Co. The interactions have been interpreted as being due to concentration of an aqueous fluid phase at the contact zone, with subsequent partial transfer into the gabbro. Zorpi *et al.* (1991) have suggested that the movement of volatiles may enhance that of certain elements and lead to the "selective enrichment" of elements such as Si, K, P, Rb, Ba, Zr and REE in the mafic rocks. Also, that the migration of such fluids will reduce the viscosity of the basic magma, enhancing the complementary effects of diffusion. D'Lemos (1992) studied interactions between granitic pipes intruding contemporaneous diorite magma. The pipes have

felsic aureoles, up to 1 m in diameter, in which textural, mineralogical and compositional effects vary systematically with distance from the granite-diorite interface. SiO_2, K_2O and Ba are noticeably enriched close to the interface. Chemical transfer from pipe to diorite, producing the aureoles, could have been accomplished by diffusion alone over the distances involved (Baker, 1991) but it is suggested that outward migration of volatile enriched residual melt played an important role. D'Lemos (1992) makes the important point that, although physical mixing between granite and diorite did not occur, textural and mineralogical features often attributed to that process have been produced by *in situ* melt modification. D'Lemos (1996) has also demonstrated that melt infiltration can cause deflection on variation diagrams from linear trends initially produced by a period of magma mixing.

These and other examples demonstrate that the type of chemical variation displayed at Sorel Point occur frequently in similar plutonic environments. In all cases, a process of volatile-enriched melt transfer has been involved to a greater or lesser extent. The fluids responsible for this at Sorel Point originated in the aplogranite and were concentrated in the granodiorite, combining with the residual liquids of the granodiorite magma prior to infiltrating the gabbroic magma. The deflection from linear trends shown by the dioritic rocks was produced by the selective nature of the infiltrational process, whereby only those components present in the residual liquids are physically transferred into the gabbroic magma. It is known (e.g. Watson and Jurewicz, 1984) that Na_2O and K_2O are highly mobile and this would account for the evidence provided by amphibole compositions, as well as the relatively high degrees of enrichment of these elements in the dioritic rocks. Enrichment in the basic magma is attended by some depletion in the acid magma, so that the contents of many elements (e.g. TiO_2, MnO, MgO, P_2O_5, Ba, La, Li) are very low in the aplogranite. This is again due to the process of chemical transfer, in which these elements are concentrated in the residual liquid and are then removed to the basic magma (c.f. Platevoet and Bonin, 1991).

CONCLUSIONS

The diorites of Group A at Sorel Point, Jersey, have been produced by interaction between coexisting granitic and gabbroic magmas, during which volatile-rich residual liquid from granitic magmas infiltrated overlying gabbroic magmas, resulting in their modification to dioritic compositions. The concentration of elements added to the gabbroic magma decreased with distance away from the granodiorite/diorite interface. Amphiboles crystallizing from the basic magma, acting as elemental scavengers, incorporated these elements, producing variations in amphibole composition. The efficiency of the infiltration process has meant that it has modified the original gabbroic magma over distances up to 14 m from the granodiorite/diorite interface. By its nature, the process of infiltration will not be uniform and this is reflected in the compositional scatter displayed by the dioritic rocks on variation diagrams. Similar interactions have occurred elsewhere throughout the complex.

ACKNOWLEDGEMENTS

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